INDOOR CARBON DIOXIDE CONCENTRATIONS AND SICK BUILDING SYNDROME SYMPTOMS IN THE BASE STUDY REVISITED: ANALYSES OF THE 100 BUILDING DATASET

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ABSTRACT

In previously published analyses of the 41-building 1994-1996 USEPA Building Assessment Survey and Evaluation (BASE) dataset, higher workday time-averaged indoor minus outdoor CO_2 concentrations (dCO_2) were associated with increased prevalence of certain mucous membrane and lower respiratory sick building syndrome (SBS) symptoms, even at peak dCO_2 concentrations below 1,000 ppm. For this paper, similar analyses were performed using the larger 100-building 1994-1998 BASE dataset. Multivariate logistic regression analyses quantified the associations between dCO_2 and the SBS symptoms, adjusting for age, sex, smoking status, presence of carpet in workspace, thermal exposure, relative humidity, and a marker for entrained automobile exhaust. Adjusted dCO_2 prevalence odds ratios for sore throat and wheeze were 1.17 and 1.20 per 100-ppm increase in dCO_2 ($p < 0.05$), respectively. These new analyses generally support our prior findings. Regional differences in climate, building design, and operation may account for some of the differences observed in analyses of the two datasets.

INDEX TERMS
Sick building syndrome, Ventilation, Carbon dioxide, Logistic regression, BASE study.

INTRODUCTION
Understanding the multifactorial etiology of sick building syndrome (SBS) in office buildings has been a major challenge. SBS is used to describe a set of symptoms with unidentified etiology frequently reported by workers in office buildings. The individuals who suffer from SBS report that the symptoms occur when they spend time indoors, particularly in office buildings, and that the symptoms lessen while away from the building (Levin, 1989; Mendell, 1993). Evidence for the hypothesis that building characteristics and resultant indoor environmental quality affects health outcomes continues to accumulate (Mendell, 1993; Fisk, 2000). These health outcomes include SBS symptoms, allergy and asthma symptoms, and respiratory illnesses. Indoor air quality also appears to influence rates of absence, work performance, and health care costs (Fisk, 2000). In this paper, we concentrate on building-related upper respiratory and mucous membrane (MM) symptoms (i.e., irritated eyes, throat, nose, or sinus), and lower respiratory (LResp) irritation (i.e., difficulty breathing, tight chest, cough, or wheeze).

The primary source of CO_2 in office buildings is respiration of the building occupants. CO_2 concentrations in office buildings typically range from 350 to 2,500 ppm (Seppänen et al., 1999). At concentrations occurring in most indoor environments, CO_2 buildup can be

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considered as a surrogate for other occupant-generated pollutants, particularly bioeffluents, and for ventilation rate per occupant, but not as a causal factor in human health responses. The Threshold Limit Value for 8-hour time-weighted-average exposures to CO_2 is 5,000 ppm (ACGIH, 1991). Currently, the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) recommends a minimum office building ventilation rate offices of 10 Ls^{-1} per person, corresponding to an approximate steady state indoor concentration of 870 ppm (ASHRAE, 1999), based on the assumptions that outdoor CO_2 is 350 ppm and indoor CO_2 generation rate is 0.31 $Lmin^{-1}$ per person.

CO_2 and SBS Studies in the Literature

In a recent review (Seppänen et al., 1999), about one-half of 22 studies of SBS symptoms in office buildings found that increased indoor CO_2 levels were positively associated with a statistically significant increase in the prevalence of one or more SBS symptoms. SBS symptoms associated with CO_2 included headache, fatigue, eye symptoms, nasal symptoms, respiratory tract symptoms, and total symptom scores. Seventy percent of studies of mechanically ventilated and air conditioned buildings found a significant association between an increase in CO_2 and SBS symptoms. Building ventilation rates were also associated with SBS symptoms. An analysis of the 94-96 BASE dataset found statistically significant dose-response relationships between dCO_2 and the following symptoms: sore throat, irritated nose/sinus, combined mucous membrane symptoms, tight chest, and wheeze; the adjusted odds ratios for these symptoms ranged from 1.2 to 1.5 per 100 ppm increase in dCO_2 (Apte et al., 2000).

METHODS

The BASE Study

The data analyzed in this paper were collected in 100 randomly selected large U.S office buildings from 1994 to 1998 by the U.S. Environmental Protection Agency for the Building Assessment Survey and Evaluation (BASE) study (Girman et al., 1995; Womble et al., 1996). These buildings were at least partially mechanically ventilated and air conditioned. BASE buildings were studied during one-week periods either in winter or summer. Environmental data were measured during the week of questionnaire administration. The BASE protocol is discussed fully elsewhere (Womble et al., 1993; BASE Website).

The BASE questionnaire confidentially collected occupant information, including sex, age, smoking status, job characteristics, perceptions about the indoor environment, and health and well-being. The SBS symptoms elicited from the questionnaire included: irritation of eyes, nose, and throat; chest tightness, difficulty breathing, cough or wheezing; fatigue; headache; eyestrain; and dry or itchy skin. To qualify as a SBS symptom in the analyses presented here, the occupant must have had a reported a symptom occurrence at least 1-3 days per week during the month previous to the study and the particular symptom must have shown improvement when the occupant was away from work.

At each office building, CO_2, volatile organic compounds (VOCs), temperature, and relative humidity (RH) were measured at three indoor locations and outdoors. CO_2 and indoor temperature were collected as 5-minute averages. VOC canister samples were collected and analyzed by gas chromatograph-mass spectrometry for 73 VOC species. Spatial-average pollutant concentrations and average temperatures were calculated based on data from the three measurement sites. Time-averaged (8 hr) workday difference between indoor and

outdoor CO_2 concentrations (dCO_2) was calculated as a surrogate measure of ventilation rate per occupant.

A thermal exposure variable (°C-hours) was calculated as the integrated difference between 5-minute-average-temperature and 20°C, normalized to 10 hours of exposure. The indoor workday-average relative humidity (RH) was calculated. The sixteen buildings with RH < 20% were excluded from the analyses discussed below, since by definition MM or LResp symptoms due to very low RH are not be considered SBS symptoms (Mendell, 1993).

Associations between BASE VOCs and SBS symptoms have been discussed elsewhere (Apte and Daisey, 1999). One VOC, 1,2,4 trimethylbenzene (TMB), found in infiltrating outdoor air and originating from automotive sources, was found to have statistically significant associations with a number of MM and LResp. Other sources of TMB in office buildings may include carpet, undercarpet, and building materials (Apte and Daisey, 1999). TMB was selected as a covariate in the regression models in order to adjust for the potential affects of ambient automotive sources on the SBS symptoms. The geometric mean TMB concentration across the 100 buildings was 0.6 ppb and the geometric standard deviation was 2.5.

Statistical Methods

Multivariate logistic regression (MLR) was used to calculate prevalence odds ratios (OR) and Wald Maximum Likelihood (WML) statistics (SAS, 1989). Crude and adjusted MLR models were constructed using continuous dCO_2 data as an independent variable and an SBS symptom as the dependent variable. Covariates used in the MLR models to control for confounding were age, sex, presence of carpet in workspace, smoking status, thermal exposure, RH, and TMB. Details regarding model building can be found in Apte et al. (2000). Additionally, a "California Buildings" covariate was added to some models.

RESULTS

Table 1 presents the results from both the crude and adjusted logistic regression analyses. The dCO_2 ORs are reported in units per 100 ppm. The larger 94-98 BASE data analysis yielded similar findings as compared with the smaller 94-96 data set, with smaller adjusted ORs ranging from 1.1 to 1.2 per 100 ppm increase in dCO_2 for Sore Throat, Nose/Sinus, and Wheeze. The effect for dry eyes observed in the smaller 94-96 dataset was not apparent in the larger 94-98 dataset.

Table 1. Crude and adjusted prevalence odds ratios[a] (OR) for dCO_2 and selected MM and LResp SBS symptoms for both the 94-96 and 94-98 BASE dataset analyses.

SBS Symptom	94-96 BASE Dataset dCO_2 OR (per 100 ppm)		94-98 BASE Dataset dCO_2 OR (per 100 ppm)	
	Crude	Adjusted	Crude	Adjusted
MM				
Dry eyes	**1.1 (1.04-1.23)**[b]	**1.2 (1.06-1.29)**[b]	1.0 (0.99-1.11)	1.0 (0.98-1.12)
Sore throat	**1.4 (1.21-1.59)**[b]	**1.5 (1.25-1.72)**[b]	**1.2 (1.09-1.31)**[b]	**1.2 (1.06-1.29)**[b]
Nose/sinus	**1.1 (1.04-1.26)**	**1.2 (1.06-1.34)**[b]	1.1 (0.98-1.14)	1.1 (0.99-1.15)
LResp				
Chest tight	1.1 (0.90-1.41)	1.3 (0.96-1.66)	1.0 (0.85-1.19)	1.0 (0.86-1.21)
Short breath	1.1 (0.87-1.37)	1.3 (0.97-1.69)	1.0 (0.87-1.24)	1.1 (0.92-1.35)
Cough	1.1 (0.91-1.23)	1.1 (0.90-1.28)	1.0 (0.86-1.07)	0.95 (0.85-1.07)
Wheeze	**1.4 (1.14-1.78)**[b]	**1.4 (1.07-1.84)**	**1.2 (1.02-1.42)**	**1.2 (1.00-1.42)**

[a]Values in parentheses are the 95% confidence interval (CI). ORs and CIs given in bold are statistically significant at the 95% confidence level or higher.
[b]$p \leq 0.005$

Preliminary analyses investigated why the results obtained from the larger 94-98 dataset differed from those obtained from the smaller 94-96 dataset. Mean levels and standard deviations of dCO_2 and the continuous covariates did not differ substantially between buildings for which data were collected in 94-96 compared with buildings for which data were collected more recently (see Table 2). Of the dichotomous covariates, only the proportion of females and older occupants differed between the two data collection periods (see Table 3). In terms of SBS symptom prevalences, the two data collection periods did not differ appreciably (see Table 3).

Table 2. Means and standard deviations for dCO_2 and continuous covariates.

Variable	94-96 BASE Buildings		97-98 BASE Buildings		P-value[a]
	Mean	SD	Mean	SD	
dCO_2 (ppm)	242	142	288	130	0.12
thermal exposure	26.16	6.84	24.37	6.94	0.25
RH	40.28	8.71	44.51	10.97	0.06
TMB	1.28	1.31	0.93	0.96	0.17

[a]Student's t-test, 2-sided

Table 3. Percent of occupants reporting selected characteristics and SBS symptoms.

Variable	94-96 BASE Buildings	97-98 BASE Buildings	P-value[a]
% female	68.0	64.8	0.04
% ≥ 40 years	53.2	57.5	0.01
% with carpet	89.9	90.5	0.50
% current smoker	15.5	14.0	0.24
% MM	27.9	26.3	0.30
% dry eyes	20.3	18.8	0.32
% sore throat	7.0	6.9	0.95
% nose/sinus	13.5	12.8	0.58
% LResp	8.8	7.7	0.29
% chest tight	2.4	2.2	0.72
% short breath	2.3	1.5	0.12
% cough	5.3	5.4	0.94
% wheeze	2.4	1.8	0.22

[a]Chi-square, Fisher's exact test, two-sided

Regional differences in climate, building codes, and other factors may account for the differences in the two analyses. For example, changes in indoor smoking policies over the BASE study period may have had an impact on factors that may be associated with SBS symptoms. One way to examine the influence of regional differences is to look at the influence of buildings from different states. Because California contributed the largest proportion of recently added buildings in 1997-1998 to the BASE study (16%), we first considered whether being in a "California Building" influenced SBS symptoms. After including the "California Building" covariate in the MLR model, the odds ratios relating dCO_2 (per 100 ppm) to the selected SBS symptoms more closely resembled those found in the analysis of the 94-96 dataset (see Table 4).

DISCUSSION

The results of these analyses indicate an association between elevated indoor CO_2 levels and increases in certain MM and LResp SBS symptoms. These findings were evident in the crude

regression models and persisted through adjustment for a number of potential confounders. After adjusting for whether a building was in California, the OR for combined MM and nose/sinus symptoms also achieved statistical significance, thus highlighting the potential importance of regional effects. Investigating specific regional differences provides an opportunity to identify building characteristics that are associated with better indoor air quality and lower SBS symptom prevalence. Subsequent analyses will employ more sophisticated models to explore the potential impact of cross-level bias.

Table 4. Adjusted prevalence odds ratios[a] (OR) for dCO_2 per 100ppm, the California building variable and selected MM and LResp SBS symptoms for the 94-98 BASE dataset analysis.

SBS Symptom	dCO_2 (per 100 ppm) OR	California Building[b] OR
MM	**1.1 (1.01-1.14)**	**1.3 (1.01-1.59)**
Dry eyes	1.1 (1.00-1.14)	1.2 (0.95-1.59)
Sore throat	**1.2 (1.09-1.35)**	1.5 (0.98-2.18)
Nose/sinus	**1.1 (1.02-1.19)**	**1.4 (1.07-1.92)**
LResp	1.1 (0.96-1.17)	1.3 (0.94-1.92)
Chest tight	1.1 (0.90-1.29)	1.8 (0.94-3.28)
Short breath	1.1 (0.91-1.38)	1.1 (0.48-2.37)
Cough	1.0 (0.85-1.09)	1.1 (0.72-1.74)
Wheeze	**1.3 (1.04-1.51)**	1.7 (0.80-3.42)

[a]Values in parentheses are the 95% confidence interval (CI). ORs and CIs given in bold are statistically significant at the 95% confidence level or higher.
[b]Estimating the association between being a "California Building" and SBS symptoms.

The odds ratios for the associations of symptoms with the maximum observed difference between indoor and outdoor CO_2 concentrations may indicate the maximum potential to reduce selected SBS symptoms in typical office buildings. The maximum value of dCO_2 was 608 ppm. Considering only the significant associations, the ORs for the maximum value of dCO_2 range from 6.7 to 7.3. Based on these ORs, the implied potential maximum reduction in prevalence of these symptoms is roughly 85%. This reduction could come through large increases in ventilation rates, improved effectiveness in providing fresh air to the occupants' breathing zone, or through identification of the symptom-causing agents in the indoor air and control of their sources. In no case were the indoor average or the peak indoor CO_2 concentrations extraordinarily high; only two buildings had peak indoor (absolute) CO_2 concentrations routinely above 1,000 ppm.

CONCLUSION AND IMPLICATIONS

After adjusting for selected covariates, we found statistically significant associations of mucous membrane and lower respiratory SBS symptoms with increasing dCO_2. Odds ratios for statistically significant associations of sore throat and wheeze symptoms with 100-ppm increases in dCO_2 were 1.1 to 1.2. These results suggest that increases in the ventilation rates per person among typical office buildings will, on average, significantly reduce the prevalence of several SBS symptoms, even when these buildings meet the existing ASHRAE ventilation standards for office buildings. The magnitude of the reduction will depend on the magnitude of the increase in ventilation rates, improvement in ventilation effectiveness, or reduction in sources of SBS-causing agents. Very large increases in ventilation rates, sufficient to reduce indoor CO_2 concentrations to approximately outdoor levels, would be expected, on average, to decrease prevalence of selected symptoms by 85%. There is no direct causal link between exposure to CO_2 and SBS symptoms, but rather CO_2 is

approximately correlated with other indoor pollutants that may cause SBS symptoms. The BASE dataset is a valuable source of U.S building information, providing an opportunity for identification of causal factors of SBS, and for development of solutions for lowering its prevalence in buildings.

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